Bioenerg. Res. (2016) 9:624–632
DOI 10.1007/s12155-015-9705-z

The Possibility of Meeting Greenhouse Energy and CO_2 Demands Through Utilisation of Cucumber and Tomato Residues

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Published online: 19 December 2015

Abstract The article examines the possibility of using residues from greenhouse cucumber and tomato cultivation as biomass for energy and CO_2 production in order to meet greenhouse needs. Methane fermentation and combustion were compared. Moreover, the legitimacy of ensiling as a storage method for biogas plant was evaluated. The tested waste was found to be an unsuitable feedstock for the production of silage due to low sugar and high protein content. Fresh waste had a higher biogas yield than silage; however, its fermentation lasted longer. Furthermore, the results showed that, in the case of fresh residues, the methane fermentation proved to be a more energy-efficient process, while air-dry biomass is a more sustainable feedstock for combustion. The energy and CO_2 balance showed that, regardless of the method used, the available quantity of waste is too small to meet the greenhouse needs.

Keywords Biogas · Greenhouse production · Combustion · Organic waste · Tomato · Cucumber

Introduction

In Poland, horticulture is a growing sector of exported raw materials. The total production of vegetables is dominated by the cultivation of tomato (810.6 thousand tonnes) and cucumber (532.0 thousand tonnes), of which as much as 538.7 thousand tonnes of tomatoes and 265.1 thousand tonnes of cucumbers were greenhouse-cultivated in 2014 [1]. Such intensive production involves huge amounts of waste in the form of shoots, stems and leaves. Boulard et al. [2] have reported that the number of greenhouse residues in France is estimated at approximately 170 t ha^{-1} of the area of greenhouses. However, it should be noted that greenhouse cultures are also characterised by a high demand for heat and carbon dioxide [3]. The annual greenhouse energy demand in Poland and other countries of Northern Europe (The Netherlands, Germany) reaches 36 TJ ha^{-1} [4, 5]. Menardo et al. [4] reported that an average greenhouse CO_2 demand is estimated to 2628 t ha^{-1}. For this purpose, greenhouses must be equipped with gas installations metering carbon dioxide in a pure form or obtain it by combustion of liquefied petroleum gas. In Poland, where rockwool is commonly used as a growing medium, enrichment of greenhouses with external CO_2 is necessary. These additional costs could be reduced via the use of anaerobic digestion or combustion of vegetable residues.

Biogas production from this type of biomass or combustion thereof could solve the problem with the disposal of waste, as well as satisfy the need for energy and CO_2. Biogas production is a multi-step process of biological decomposition of organic matter. It consists of the following phases: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Each involves various species of microorganism. Biogas contains mainly CH_4 and CO_2 and small amounts of hydrogen, ammonia and hydrogen sulphide [6]. The most common substrate for biogas production is maize silage, especially in central Europe, due to its high biomass yield per hectare (20–30 t TS ha^{-1}) [7]. In Poland, the mean maize yield in 2014 was ca. 47.8 t fresh matter ha^{-1} [1]. High yield, adequate availability and high methanogenic potential make it the most desirable substrate [8]. However, because of the threat of monoculture and rising prices, it is necessary to search for a worthy alternative to this material. Many various energy crops that could

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successfully replace corn, such as organic waste, energy crops [6], and even microalgae [9], have been tested. The high potential of waste is increasingly emphasised, which is primarily due to the low cost of obtaining them and the possibility of simultaneous utilisation. In addition to municipal and kitchen waste, a large part of this group is constituted by waste from agricultural and horticultural production [10–12]. Agricultural residues could also be suitable biomass for combustion. The calorific values, low moisture and a low concentration of ash, nitrogen (N), sulphur (S), potassium (K) and sodium (Na) are the main aspects determining the suitability. The calorific value of residues can be expressed as follows: higher heating value (HHV), lower heating value of dry biomass (LHV_d) or lower heating value of wet biomass (LHV_w) [13]. HHV is defined as the amount of heat released when fuel is combusted and the products have returned to a temperature of 25 °C; thus, it takes into account heat associated with water condensation. LHV_d is determined by subtracting the heat of vaporisation of water generated during combustion of fuel and taking into account mainly the hydrogen content in biomass. LHV_w is equal to LHV_d reduced by heat of vaporisation of water present in biomass before combustion.

A high concentration of N and S causes pollutant emissions. Alkali and alkaline earth metals, especially K and Na, are involved in slagging processes and fouling of the combustion chamber and the heat exchanger surfaces by reducing the ash melting temperature [14]. More desirable is the presence of calcium (Ca) and magnesium (Mg), because their mobility and the properties of the deposits it forms are both more favourable to sustained furnace operation [15].

The issue of greenhouse residue disposal was a subject of many studies. Generally, the composting process was investigated as a useful alternative for waste management [16, 17]. The vast majority of studies on the cucumber and tomato methane fermentation process concerned fruits unfit for consumption, rather than green parts of plant such as the leaves, stems and stalks [18, 19]. Few studies on the biogas production from greenhouse residues prove that it is worthy of interest substrate [7]. No studies have been conducted on the ensiling this kind of waste and methane fermentation of such silages. Jagadabhi et al. [7] stated that greenhouses could collect and utilise these crop residues for biogas production and in turn meet their own energy demand, but no attempts have been made to compare the energy produced from this raw material and greenhouses energy demand in the country or region scale. Furthermore, carbon dioxide production as a valuable raw material for greenhouses has not been investigated. The comparison of methane fermentation and combustion as the methods of energy and CO_2 production is also not carried out in previous studies.

Hence, the aim of this study was to evaluate the possibility of disposal of greenhouse cucumber and tomato residues through heat and CO_2 production by methane fermentation or combustion. Moreover, the suitability of tomato and cucumber waste for silage was analysed given a possible need of storage thereof in a biogas plant.

Materials and Methods

Material

The stems, leaves and stalks remaining after the cultivation of cucumber and tomato under cover were the tested material. The material came from the Chair of Plant Horticulture and Fertilisation, University of Life Sciences in Lublin. The seeds of cucumber were sown in February 2013, and then, seedlings were planted in their permanent place in March 2013 at the density of one plant for 1 m^2. Completion of cultivation occurred in July 2013. The tomato was grown from February to October 2013 at the density of 2.4 plants for 1 m^2. Plants protection treatments and cultivation were performed in accordance with the relevant recommendations. Rockwool was used as a growing medium. Drip fertigation method was applied in closed system without recirculation of nutrient solution that contained essential macrocomponents and microelements. *Bombus terrestris* was used for plant pollination, and greenhouse whitefly (*Frialeurodes vaporariorum*) was biologically controlled with *Encarsia formosa*. Fruit picking was performed 2–3 times a week [20]. Approximately 15 kg of fresh residues of each species were wilted up to moisture of approximately 75 % and were broken down to fractions of approximately 20 mm. Two kilograms of such biomass were directly subjected to analysis, and the rest of material was previously ensiled in 5-L airtight barrels in three independent replications, in ambient temperature of 22 °C, for approximately 60 days. As a silage additive, Biosilac produced by Bio-Gen was used. In accordance with the manufacturer's recommendations, 1 L of solution with a concentration of 50 g L^{-1} was prepared and applied by atomiser on each layer of residues. Biomass has been thoroughly compacted to get rid of air.

Chemical Analysis

The fresh and ensiled material was physico-chemically tested for the content of total solids (TS), volatile solids (VS) and ash with a weight-drier according to PN-EN 12880 and PN-EN 12779, the total organic carbon (TOC) content with a TOC-V CPN analyser with a Solid Sample Combustion Unit SSM-5000A in accordance with the manufacturer's protocol, pH with potentiometry, the content of simple sugars with the Luff–Schoorl method and nitrogen with the Kjeldahl method. Crude protein (CP) was calculated by multiplying the nitrogen content by a coefficient of 6.25. Ammonium nitrogen N_{NH4} was determined by spectrophotometry and macroelements by

ICP OES following the procedure described by Oleszek et al. [21]. Based on the results of the macroelements analysis, the alkali index (I_a) is calculated as Jenkins et al. [15]:

$$I_a = \left(1 / Q\right) Y_a \left(Y_{Na2O} + Y_{K2O}\right) \tag{1}$$

in which Q is the higher heating value (HHV) [GJ kg^{-1}], Y_a is the mass fraction (dimensionless) of ash in the fuel, Y_{K2O} and Y_{Na2O} are the mass fractions (dimensionless) of K_2O and Na_2O in the ash.

Biogas Production

Methane fermentation was performed in set of six eudiometers with working volume of 1 L, according to VDI 4630 (2006). The parameters of batch assay were as follows: temperature of 37 °C, pH ca. 7, initial loading of 60 g VS L^{-1}, substrate to inoculum ratio (S/I) of 1:1 (based on the VS). Post-fermentation sludge from a mesophilic, agricultural biogas plant was used as the inoculum, utilising corn silage and whey as the substrates. pH, TS and VS of inoculum were 7.6, 3.8 and 2.5 %, respectively. The volume of biogas was determined by the method of displacement of liquid, which was acidified and saturated solution of sodium sulphate [22]. Once a day, the methane concentration was measured by an automated analyser. Daily methane yield was determined through multiplying daily biogas yield and daily methane content. Overall methane content was determined as a ratio of total methane yield and total biogas yield. The process was carried out until the daily yield was lower than 1 % of the previous total biogas yield. The values of measured biogas volume were converted into standard conditions (1013 mbar, 273 K). The study was performed in three independent replications of fresh and ensiled residues and inoculum as a control. Then, biogas yield of inoculum was subtracted from biogas yield of tested samples.

The amount of heat energy that can be obtained through the methane fermentation process (q_{FM}) was calculated according to the formula:

$$q_{FM} = 0.8 \left(Y_M \times \mathrm{LHV}_M\right) \tag{2}$$

where: q_{FM}—heat energy from a unit of mass of cucumber or tomato residues [MJ kg^{-1}], Y_M—methane yield of tomato or cucumber residues [m^3 kg^{-1} TS], LHV$_M$—lower heating value of methane (36 MJ m^{-3}), 0.8—result of the subtraction of 20 % of heat from biogas required to meet own demands of the biogas plant [23].

Combustion

The HHV of the residues was tested using a calorimeter LECO model AC600 with ACWin Software in accordance with the manufacturer's protocol. Before calorimetric analysis, samples of tomato and cucumber residues were dried, milled and formed into tablets using a tablet press. Lower heating value (LHV) was calculated in accordance with PN-80/G-04511 and PN-ISO 1928. LHV was calculated at moisture level of 0, 25 and 75 %. The second value of moisture is characteristic for air-dried waste and the latter for waste which was used for biogas production.

Energy and CO_2 Balance

A simple energy and CO_2 balance calculation was conducted by comparison of the results of methane production and combustion and greenhouse demands. In order to estimate the annual heat (D_Q) and CO_2 (D_{CO2}) demands of greenhouses in Poland and the total annual amount of cucumber and tomato residues in Poland (based on TS and fresh matter (FM)) (M_W), the following assumptions were made:

- Annual heat demand per unit of area (D_Q)—36.1 TJ ha^{-1} of greenhouses [4].
- Annual carbon dioxide demand per unit of area (D_{CO2})—2628 t ha^{-1} [4].
- Average annual amount of fresh waste per unit of area (m_w)—170 t ha^{-1} [2]. The TS content of waste was taken from the results of chemical analyses.
- Area of cucumber and tomato greenhouse cultivation in Poland (A)—1229.1 and 2170.8 ha [1].

The calculations were conducted in accordance with the formulas:

$$D_Q = d_Q \times A \tag{3}$$

$$D_{CO2} = d_{CO2} \times A \tag{4}$$

$$M_W = m_w \times A \tag{5}$$

In the next step, the amount of heat that can be produced in the methane fermentation and combustion process (Q_{FM} and Q_C, respectively) for a specified amount of waste in Poland (M_w) was determined according to the formulas:

$$Q_{FM} = q_{FM} \times M_w \times 10^{-6} \tag{6}$$

where: Q_{FM}—annual heat energy from available amounts of residues [PJ a^{-1}], q_{FM}—heat energy from unit of mass of cucumber or tomato residues [MJ kg^{-1}], M_w—annual amount of residues in Poland [t a^{-1}]

$$Q_C = \mathrm{LHV} \times M_W \times 10^{-6} \tag{7}$$

where, Q_C—heat from combustion [PJ], LHV—lower heating value of residues [MJ kg^{-1}], M_W—annual amount of residues in Poland [t a^{-1}].

To calculate the amount of carbon dioxide formed in the methane fermentation process ($CO2_{FM}$), the following statements and assumptions have been applied:

- Biogas is composed of methane and carbon dioxide
- Methane is subjected to complete combustion
- According to the stoichiometry of the reaction equation, from complete combustion of 1 dm^3 of methane, 1 dm^3 of carbon dioxide is produced

This means that the final carbon dioxide volume after biogas combustion is approximately equal to the biogas volume obtained during the fermentation process (Y_{bio}) (disregarding trace amounts of other gases).

The volume established in this manner was converted to mass:

$$co2_{FM} = Y_{bio,} \times P_{CO2} \tag{8}$$

$$CO2_{FM} = co2_{FM} \times M_W \tag{9}$$

where: $co2_{FM}$—mass of carbon dioxide produced from methane fermentation per unit of mass of residues [t t^{-1} TS], $CO2_{FM}$—annual mass of carbon dioxide produced from methane fermentation of cucumber or tomato residues in Poland [t a^{-1}], Y_{bio}—biogas yield of cucumber or tomato residues, respectively [m^3 t^{-1} TS], P_{CO2}—density of carbon dioxide (1013 mbar, 293 K) [t m^{-3}], M_w—annual amount of residues in Poland [t a^{-1}]. $CO2_C$ was calculated as follows:

$$co2_C = C \times 3.67 \tag{10}$$

$$CO2_C = co2_C \times M_w \tag{11}$$

where: $co2_C$—mass of carbon dioxide per unit of mass of waste [kg kg^{-1} TS], $CO2_C$—annual mass of carbon dioxide produced from combustion of cucumber or tomato residues in Poland [t a^{-1}], C—carbon content in residues [%], M_W—annual amount of residues in Poland [t a^{-1}], 3.67—stoichiometric factor

Statistical Analysis

Statistical analysis was performed using STATISTICA 10. The results of the chemical analysis, methane fermentation and combustion were expressed as the mean ± standard deviation (SD) of three independent replicates. The effects of species and ensiling were tested by two-way analysis of variance. Tukey's test was applied as a post-hoc test. Student's t test was performed to compare content of macroelements in fresh cucumber and tomato residues and energy and CO_2 production by methane fermentation and combustion. The level for accepted statistical significance was $p < 0.05$.

Results and Discussion

Chemical Analysis

The results of physicochemical analyses are presented in Table 1. Cucumber residues yielded much lower TS compared to tomato residues. However, in both cases, they were below the norm for silage fresh matter. Literature data suggest that the optimum dry matter content of silage forage should be approximately 25–40 % [24]. Insufficient content leads to mass loss in the form of juice leakage [25]. On the other hand, Beaulieu et al. [26], who studied influence of dry matter on silage quality using standard methods, reported that excess content prevents adequate compaction and removal of air. For this reason, too wet biomass must be wilted before ensiling. The process of silaging decreased the TS, VS, nitrogen and protein content. Loss of nutrients in silage is an unfavourable phenomenon associated with metabolic processes e.g. respiration of plants or the growth of yeast and *Clostridium* sp. [27]. As it has been stated by McEniry et al. [28] in their study of Timothy silage, proteolytic clostridial activity caused high pH and high concentration of butyric acid and ammonia-N. The high pH and high concentrations of N_{NH4} of tested silages may indicate proteolytic clostridial activity, but concentration of butyric acid has not been determined. The content of nitrogen and protein in the examined waste was significantly higher, and the content of sugar was lower than in other typical silage plants. For example, Amon et al. [8], using Kjeldahl method, stated that maize contains 5.9–10.1 % of proteins. The poor rate of the ensiling process was also manifested by an unpleasant odour. A feedstock with such quality does not meet the requirements for silage [29]. The low C/N ratio is a poor prognostic factor for the fermentation process, since the optimum is 25–30 [30]. However, some literature reports provide examples of effective common biogas production, despite the poor quality of silage. This can be explained by the fact that poor quality silage often contains ethanol and butyric acid, which have a higher theoretical biogas yield (693 L CH_4 kg^{-1} and 604 L CH_4 kg^{-1}, respectively) compared to acetic acid and lactic acid (each with 355 L CH_4 kg^{-1}) [28].

Methane Fermentation

The results indicate that the fermentation of fresh tomato residues was most effective (606.9 ml g^{-1}VS), while ensiled cucumber waste was least effective (327.3 ml g^{-1} VS) (Table 2). The results of methane yield of fresh tomato and cucumber residues are in accordance with Jagadabhi et al. [7] who found similar methane yield of tomato and cucumber shoots in the two-stage anaerobic digestion. In this study, ensiled wastes began to ferment faster than fresh matter, and their fermentation was completed sooner (Figs. 1 and 2). This

Table 1 Chemical and physical properties

	Unit	Cucumber residues		Tomato residues	
		Fresh	Ensiled	Fresh	Ensiled
TS	[% FM]	10.77 ± 1.11^{a}	23.50 ± 2.22^{b}	17.42 ± 0.54^{c}	23.09 ± 0.29^{b}
VS	[% TS]	74.70 ± 7.17^{a}	66.27 ± 2.15^{b}	81.97 ± 0.41^{c}	82.24 ± 0.34^{c}
Ash	[% TS]	25.30 ± 7.17^{a}	33.73 ± 2.15^{b}	18.03 ± 0.41^{c}	17.76 ± 0.34^{c}
C	[% TS]	52.64 ± 0.81^{a}	50.89 ± 1.21^{a}	53.00 ± 1.93^{b}	49.90 ± 0.61^{a}
$N_{tot.}$	[% TS]	4.38 ± 0.16^{a}	2.75 ± 0.01^{b}	3.47 ± 0.13^{c}	2.50 ± 0.02^{d}
N_{NH4}	[% TS]	0.54 ± 0.04^{a}	1.58 ± 0.08^{b}	0.33 ± 0.05^{c}	1.17 ± 0.04^{d}
C/N		12.01 ± 021^{a}	18.51 ± 0.12^{b}	15.27 ± 0.24^{c}	19.96 ± 0.07^{d}
CP	[% TS]	27.38 ± 1.0^{a}	17.19 ± 0.63^{b}	21.69 ± 0.81^{a}	15.63 ± 1.25^{c}
Total sugars	[% TS]	1.85 ± 0.11^{a}	1.15 ± 0.05^{b}	1.65 ± 0.09^{a}	1.09 ± 0.02^{c}
pH		7.20 ± 0.09^{a}	6.63 ± 0.03^{b}	6.29 ± 0.18^{c}	4.77 ± 0.01^{d}
Ca	[% TS]	3.09 ± 0.01^{a}	–	1.81 ± 0.03^{b}	–
K	[%TS]	6.39 ± 0.00^{a}	–	3.96 ± 0.05^{b}	–
Mg	[%TS]	0.47 ± 0.00^{a}	–	0.51 ± 0.06^{b}	–
Na	[%TS]	0.07 ± 0.01^{a}	–	0.06 ± 0.00^{b}	–
S	[%TS]	0.61 ± 0.02^{a}	–	1.02 ± 0.02^{b}	–
Alkali index	[kg GJ^{-1}]	0.82 ± 0.09^{a}	–	0.23 ± 0.05^{b}	–

Mean values with different superscript letters within row differ significantly ($p < 0.05$)

TS total solids, *FM* fresh matter, *VS* volatile solids, $N_{tot.}$ total nitrogen, N_{NH4} ammonium nitrogen, *CP* crude protein

was confirmed by Kafle and Kim [31] who, using similar methods of batch assay, studied influence of chemical composition and ensiling on biogas yield from various kind of waste such as Chinese cabbage, fish, bread and apple waste. These authors recommended ensiling as a good method for storage of agricultural by-products.

Table 2 Biogas, methane and carbon dioxide production

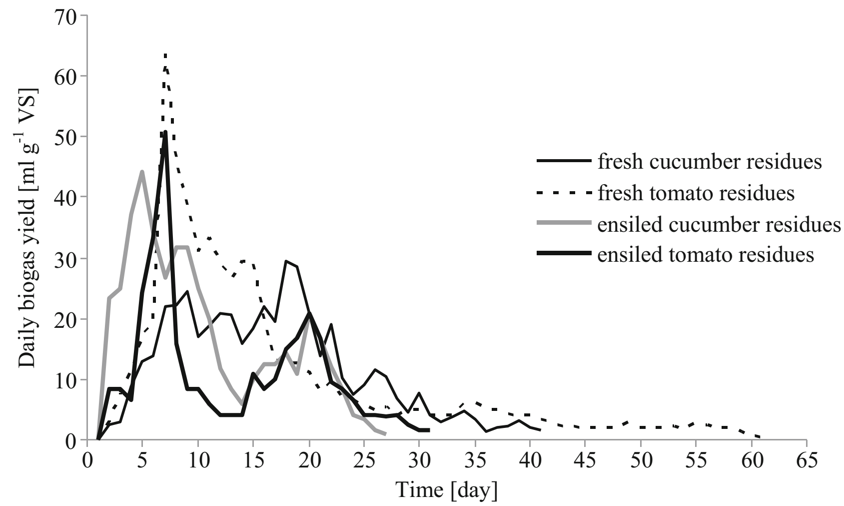
	Unit	Cucumber residues		Tomato residues	
		Fresh	Ensiled	Fresh	Ensiled
Biogas	[m^3 t^{-1} FM]	39 ± 1^{a}	40 ± 2^{a}	90 ± 2^{b}	31 ± 1^{c}
Biogas	[m^3 t^{-1} TS]	363 ± 6^{a}	270 ± 7^{b}	515 ± 11^{c}	300.4 ± 9^{d}
Biogas	[m^3 t^{-1} VS]	474 ± 8^{a}	327 ± 10^{b}	607 ± 13^{c}	453 ± 15^{a}
CH_4	[m^3 t^{-1} FM]	23 ± 1^{a}	21 ± 1^{b}	45 ± 1^{c}	17 ± 1^{d}
CH_4	[m^3 t^{-1} TS]	215 ± 4^{a}	137 ± 3^{b}	255 ± 4^{c}	158 ± 4^{d}
CH_4	[m^3 t^{-1} VS]	280 ± 5^{a}	166 ± 4^{b}	301 ± 5^{c}	238 ± 7^{d}
CH_4	[%]	59 ± 2^{a}	51 ± 2^{b}	50 ± 1^{b}	52 ± 2^{b}
CO_2	[m^3 t^{-1} FM]	16 ± 1^{a}	20 ± 1^{b}	45 ± 1^{c}	15 ± 1^{a}
CO_2	[m^3 t^{-1} TS]	146 ± 7^{a}	131 ± 3^{b}	257 ± 5^{c}	141 ± 3^{a}
CO_2	[m^3 t^{-1} VS]	191 ± 5^{a}	159 ± 5^{b}	302 ± 6^{c}	212 ± 9^{d}
CO_2	[%]	40 ± 2^{a}	49 ± 1^{b}	50 ± 1^{b}	47 ± 1^{c}

Mean values with different superscript letters within row differ significantly ($p < 0.05$)

FM fresh matter, *TS* total solids, *VS* volatile solids

As reported by Jagadabhi et al. [7], better hydrolysis and solubilisation rate of ensiled substrates can be explained by their lower pH, as the optimal pH for hydrolysis is 4–6. Rapid beginning of the methane fermentation can be also related to the initial decomposition of biomass occurring during the ensiling process, making it easily accessible to bacteria. The excess concentration of simple compounds already at the outset of the process sometimes makes microorganisms unable to utilise quickly enough volatile fatty acids that accumulate within a short time. This leads to acidification as well as collapse and faster completion of the process, resulting in a lower biogas yield. Similar results was obtained by Kandel et al. [32] who observed that rapid fermentation of non-structural components in young biomass of reed canary grass can cause a small build-up in acid products and partial inhibition of the process. Also, Ward et al. [33] highlighted that rapid hydrolysis of simple compounds may lead to acidification of a digester and consequent inhibition of methanogenesis, which takes place particularly in the case of fruit and vegetable wastes. Acidification in this study was manifested by decrease in biogas yield between the first and second peak of methane fermentation (Fig. 1) and characteristic inflexion of the curve shown in Fig. 2. This decrease is greater for ensiled residues than for fresh ones. Volatile fatty acids (VFA) accumulated at this stage, are then direct reason of the second peak between 15th and 25th day of the batch assay. About two peaks of methane fermentation was reported also by Wagner et al.

Fig. 1 Daily biogas yield



[34] and Oleszek et al. [22], who gave accumulation of VFA as a reason for this phenomenon.

Despite the rapid beginning if batch assay, both silage matters gave significantly lower ($p < 0.05$) total biogas and methane yield than fresh substrates. Apart from acidification, this can be explained also by poor quality of silages.

The best quality of biogas was obtained from fresh cucumber waste (59.1 % average methane concentration of biogas), significantly better than ensiled one. No significant difference was observed between fresh and ensiled tomato residues. Methane concentration in biogas depends on chemical composition of substrate and can be predicted based on the C:H:O:N ratio [35]. Jacobi et al. [36] reported that the methane concentration from sugars, proteins and fats is 50, 70–71 and 67–68, respectively. Figure 3 shows methane concentration of the biogas produced throughout the first 40 days of the batch assay. Fresh residues characterised by higher methane concentration at the beginning of the batch assay than ensiled ones. These results are in accordance with data reported by Kandel et al. [33], who pointed out that the first week of methane fermentation of biomass rich in non-structural and soluble carbohydrates was characterised by lower methane concentration than biomass with higher content of neutral detergent fibre (NDF). Additionally, methane content in biogas is also dependent on the pH, which affects the solubility of CO_2 and H_2S (norm VDI 4630). At low pH, lower solubility of these gases causes their higher concentration in the headspace.

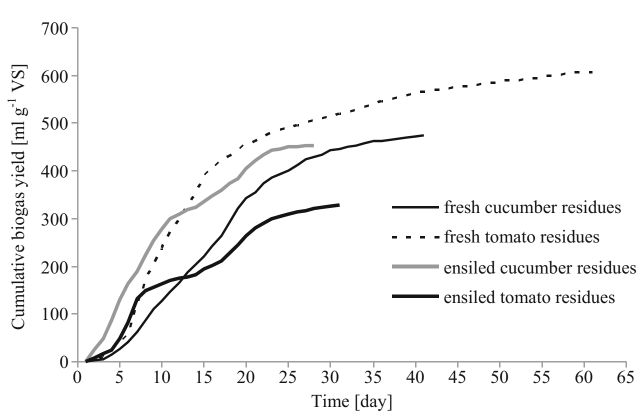


Fig. 2 Cumulative biogas yield

Energy and CO_2 Production by Methane Fermentation and Combustion

HHV and LHV of the tested residues are presented in Table 3. HHV are slightly lower than or similar to other agricultural waste. For example, Skoulou and Zabaniotou [37] reported that HHV of rice straw, vineyard prunings, tobacco stems, wheat straw, sugar beet leaves and corn stalks is 12.1, 16.8, 16.1, 17.9, 17.7, and 17.8 MJ kg^{-1}, respectively. Similar result of HHV of 14.1 MJ kg^{-1} for greenhouse residues was obtained by Us and Perendeci [38] based on the ASTM D5865-10a method.

In present study, LHV was compared with q_{FM}. LHV depends on moisture, which often limits the suitability of biomass for combustion. The problem of moisture does not occur in the case of methane fermentation. It can be seen that residues with moisture of 75 % are a more suitable feedstock for biogas production than for combustion. Their $q_{FM,75}$ is higher than LHV_{75}. However, the use of air-drying proved to be sufficient to increase LHV of the tested residues and made combustion a more energy-efficient process than methane fermentation (LHV_{25} was significantly higher than $q_{FM,\ 25}$, $\alpha < 0.05$).

Furthermore, the analysis of macroelements has shown that cucumber and tomato residues contain a high concentration of ash, K, Na, Ca and S and have a high alkali index (Table 4). According to Miles et al. [39], above 0.17 kg alkali GJ^{-1} fouling is very possible, and above 0.34 kg GJ^{-1} fouling is almost certain to occur. This proves that this kind of biomass,

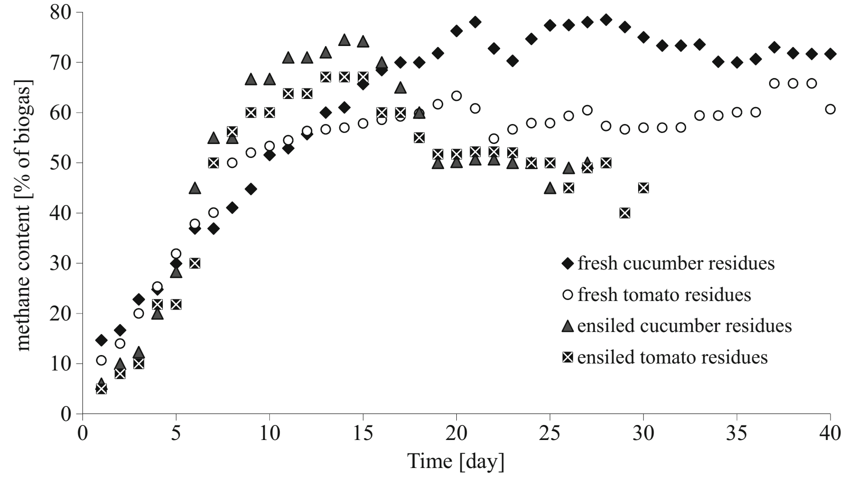


Fig. 3 Methane concentration of the biogas produced throughout the first 40 days of the batch assay

particularly cucumber waste, has a poor quality for combustion and involves a risk of damage to power plant installation. This is a major disadvantage of combustion in comparison to methane fermentation.

The most important disadvantage of methane fermentation process is the high investment cost of approximately 5000 EUR/kW for smaller and 3800 EUR/kW for bigger biogas plants. Furthermore, because of the many sources of costs and revenues and amending the law relating to the system of support, the calculation of the profitability of agricultural biogas plant construction, especially on a small scale, is quite complicated [40].

Taking into account the operating costs of biogas production from various substrates, use of waste is widely regarded as the most economical solution, due to the lack of the need for purchase of substrate. Vegetable residues are free feedstocks; thus, their use significantly improves the economic balance of the process. For comparison, the cost of maize silage ranges from 120 to 160 PLN per tonne [40]. Iglinski at al. [41] compared the profitability of biogas production from waste (slurry, slaughter waste, municipal solid waste) and maize silage. Economic balance of biogas production from maize silage turned out to be negative, due to the high cost of this feedstock. Green biomass from natural grasslands, gardens and parks is cheap, and the use of it for energy production would not affect food prices. Despite that, the energy yield of such biomass is variable because the harvested plant material is diverse in terms of both plant species and chemical composition and very often contains a lot of fibre [42]. However, in the case of waste, very important is their sufficient amount in the place of use, lack of spatial dispersion of substrate, which would result in the need for the collection and transport over long distances. For example, due to the scattered nature of bio-waste sources as well as a low degree of waste segregation in Poland, the technical biogas potential from municipal waste can be estimated at the level of 10 % of the theoretical potential 10 million m^3 of biogas (1 PJ) [41]. Therefore, the most reasonable is the construction of biogas plant nearby both producer of substrate and energy consumers. Greenhouses meet both conditions simultaneously. Alternatively, greenhouse collaboration with external biogas plant located within a short distance may be considered.

Table 4 shows the calculated amount of CO_2 produced by methane fermentation and combustion. The amount of CO_2 formed by combustion is much higher than that yielded by methane fermentation, due to the fact that some carbon remains in the digestate as a component of non-degradable compounds. Menardo et al. [4] also evaluated the possibility of producing energy and CO_2 for greenhouse needs, but *Miscanthus*, untreated and pretreated with the stream

Table 3 Amount of energy produced per unit of mass of residues by methane fermentation and combustion, at a moisture level of 0, 25 and 75 %

	Unit	Cucumber residues	Tomato residues
HHV	[MJ kg^{-1}]	12.00 ± 0.53^a	13.58 ± 0.47^b
LHV_0		11.12 ± 0.53^a	12.60 ± 0.47^b
LHV_{25}		7.73 ± 0.40^a	8.84 ± 0.35^b
LHV_{75}		0.95 ± 0.13^a	1.32 ± 0.12^b
$q_{FM.\ 0}$		6.18 ± 0.44^a	7.35 ± 0.52^b
$q_{FM.\ 25}$		4.63 ± 0.33^a	5.51 ± 0.39^b
$q_{FM.\ 75}$		1.54 ± 0.11^a	1.84 ± 0.13^b

Mean values with different superscript letters within row differ significantly ($p < 0.05$)

Table 4 Amount of CO_2 produced per unit of mass of residues by methane fermentation and combustion

	Unit	Cucumber residues	Tomato residues
$CO2_{FM}$	kg kg^{-1} TS	0.71 ± 0.02^a	1.01 ± 0.02^b
$CO2_C$		1.97 ± 0.03^a	1.94 ± 0.04^a

Mean values with different superscript letters within row differ significantly ($p < 0.05$)

explosion method, was used as a substrate. The amount of energy and CO_2 produced by methane fermentation of the untreated *Miscanthus* was 2.37 MJ kg^{-1} TS and 0.25 kg kg^{-1} TS and that of the pretreated *Miscanthus* was 9.76 MJ kg^{-1} TS and 1.15 kg kg^{-1} TS, respectively. These values include loss of energy needed for the cultivation of this plant, which is not necessary in the case of waste.

Energy and CO_2 Balance

The demands of Polish greenhouses for heat and carbon dioxide and the amount of waste that they generate are presented in Table 5. The amount of dry waste per hectare (18.3 t TS of cucumber and 29.6 t TS of tomato residues) can be larger than the dry yield of typical energy crops, such as maize [1, 8]. The total annual amount of cucumber and tomato fresh waste in Poland is estimated at 577.9 thousand tonnes. This huge part of valuable biomass could be utilised.

Heat energy that can be obtained by methane fermentation of such an amount of residues is calculated at ca. 0.511 PJ and by combustion from 0.425 to 1.060 PJ, depending on the moisture. Unfortunately, all of the above-mentioned values are significantly lower than the domestic greenhouse energy demand. As reported by Shul [5], only in the Lubelskie Voivodeship, where there were 47 ha of crops under cover in 2002, the annual demand for energy for greenhouse heating was approximately 59 thousand tce (ton of coal equivalent), which is equal to 1.7 PJ. For comparison, the total theoretical potential of the primary energy production from biogas in the Lubelskie Voivodeship is estimated at 172 PJ but as many as 167 PJ of this amount belongs to energy crops [40].

Additionally, the amount of the produced carbon dioxide turned out to be much lower than the demand. These results are consistent with previous calculations of Menardo et al. [4]. The balance showed that the use of such waste biomass could be interesting for greenhouse use in Poland, but only in combination with another supplementary energy source.

Table 5 Energy and CO_2 balance

	Unit	Cucumber residues	Tomato residues
M_w	tys. tonnes FM a^{-1}	208.9	369.0
	tys. tonnes TS a^{-1}	22.5	64.3
D_Q	PJ a^{-1}	44.2	78.1
Q_{FM}	PJ a^{-1}	0.139	0.472
$Q_{C.\ 75\ \%}$	PJ a^{-1}	0.086	0.339
$Q_{C.\ 25\ \%}$	PJ a^{-1}	0.232	0.758
$Q_{C.\ d}$	PJ a^{-1}	0.250	0.810
D_{CO2}	tys. tonnes a^{-1}	3230.0	5704.9
CO_{2FM}	tys. tonnes a^{-1}	16.0	64.9
CO_{2C}	tys. tonnes a^{-1}	43.4	125.0

Conclusions

The results imply that the wastes of cucumber and tomato cultivation provide a suitable feedstock for methane fermentation, but unsuitable material for silage. Both methane fermentation and combustion are good options for greenhouse residue disposal as well as production of heat and carbon dioxide for greenhouse needs. More energy can be obtained in combustion than through the methane fermentation process, but energy-intensive drying is required, and a risk of fouling and slagging can occur. Despite the fact that the annual amount of residues is too small to be able to meet the total greenhouse heat and CO_2 demands, potential of such biomass should be taken into account. Additional study in continuous system of methane fermentation and larger scale are recommended for practical application purpose.

Acknowledgments The authors would like to express thanks to the employees of the Chair of Plant Horticulture and Fertilization, University of Life Sciences in Lublin, for providing the material for investigations.

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